LIINES Capabilities & Insights for the NIST Transactive Energy Challenge

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LABORATORY FOR INTELLIGENT INTEGRATED NETWORKS OF ENGINEERING SYSTEMS
EMPOWERING YOUR NETWORK

Massachusetts Institute of Technology

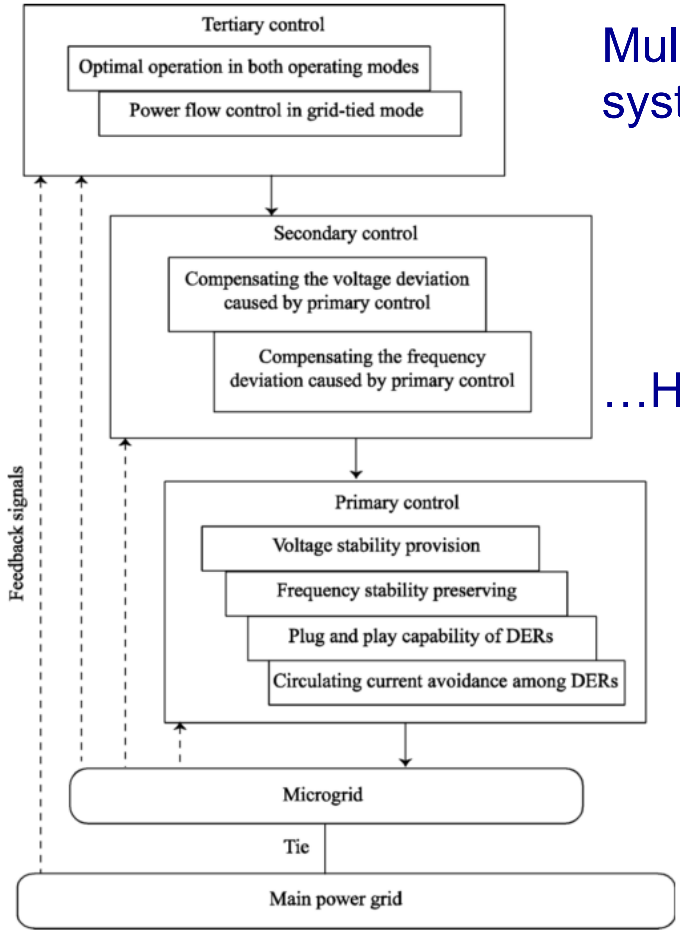
THAYER SCHOOL OF ENGINEERING AT DARTMOUTH

Presentation Outline

Goal: To highlight several LIINES' capabilities & insights relevant to the transactive energy challenge

- **Capabilities**
  - Power Grid Enterprise Control Simulator
  - Resilient Smart Grid Simulator
  - Multi-agent smart grid control platform
- **Insights**
  - Cost optimality does not guarantee system stability
  - System stability does not guarantee cost optimality
  - Negotiated equilibria does not guarantee cost optimality
  - Distributed decision making does not guarantee resilience
  - Switching decisions require real-time control to guarantee transient stability

Need for Power Grid Enterprise Control



Multiple time scales addressed by ***separate*** power system control layers

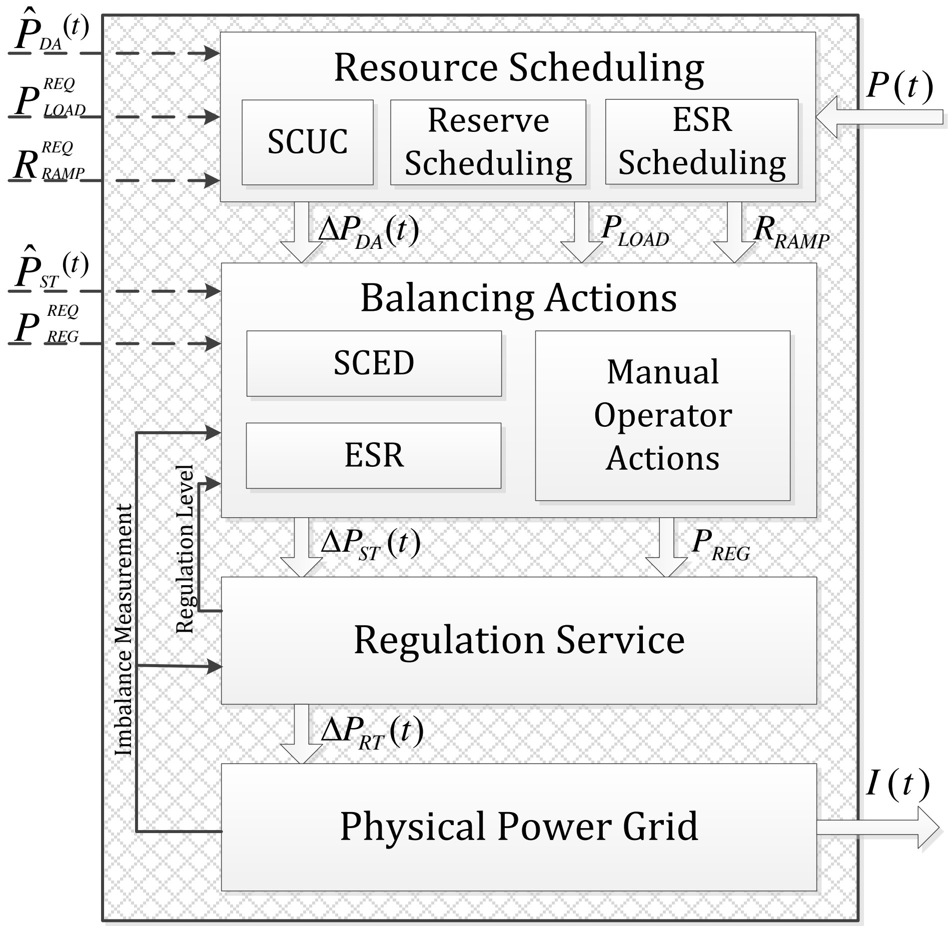
- Primary control → AGC, AVR
- Secondary control → operations control center including manual actions
- Tertiary control → energy markets

…However,

- Renewable energy integration introduces dynamics at all time scales
- FERC has changed frequency requirements on real time markets from 1hr to 15 minutes. PJM-ISO uses 5 minutes
- German TSO 50Hz finds manual operators are making more frequent adjustments (especially curtailment)
- Grid scale storage & smart building move transients into slower time scales

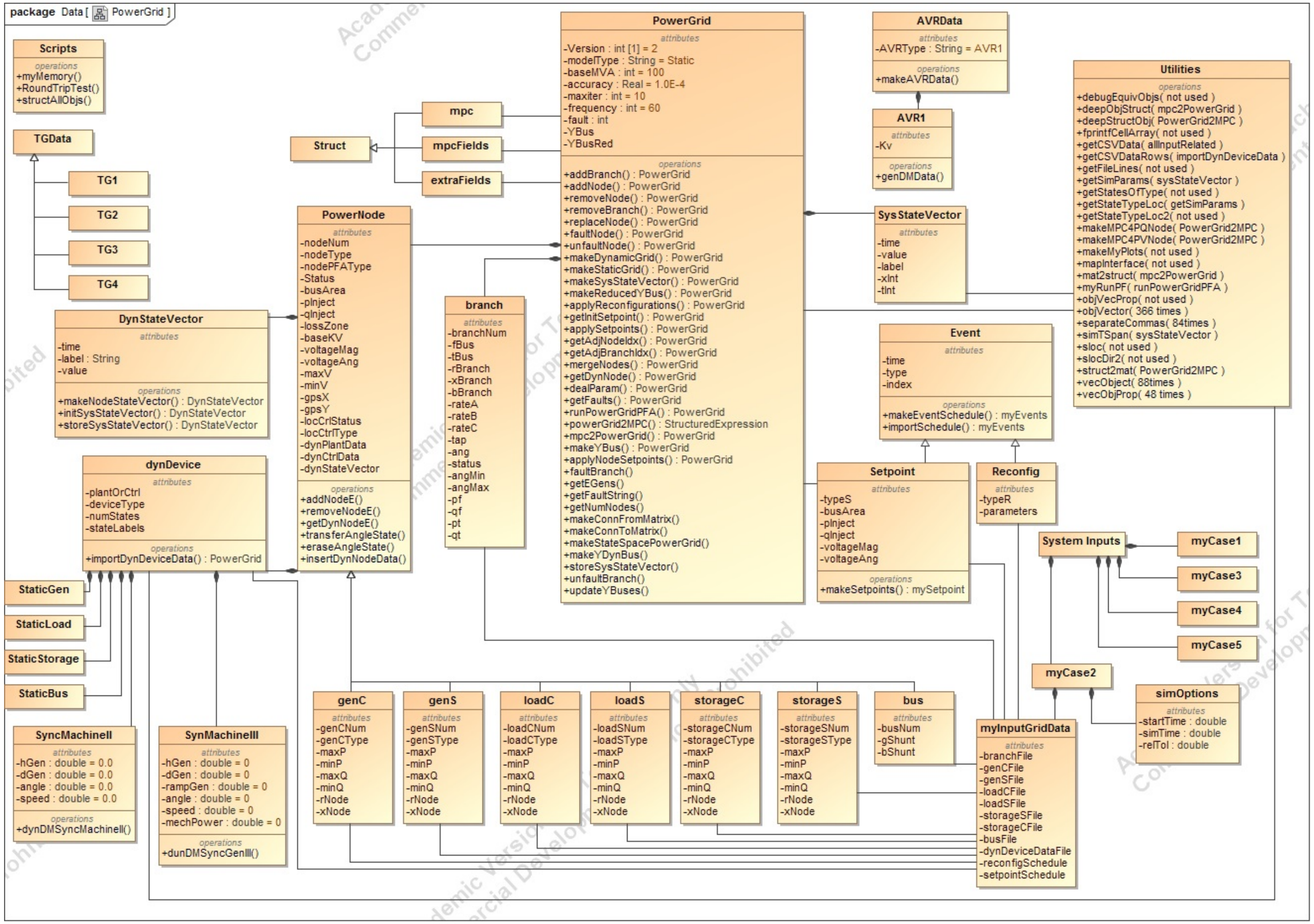
∴ Primary, Secondary & Tertiary Control are increasingly intertwined

Power Grid Enterprise Control Simulator



∴ Reconfigurable multi-layered multi-time horizon control, automation, & optimization system for holistic power system analysis

Resilient Smart Grid Simulator



∴ **Fully object-oriented to support reconfigurable & resilient operation on the fly!**

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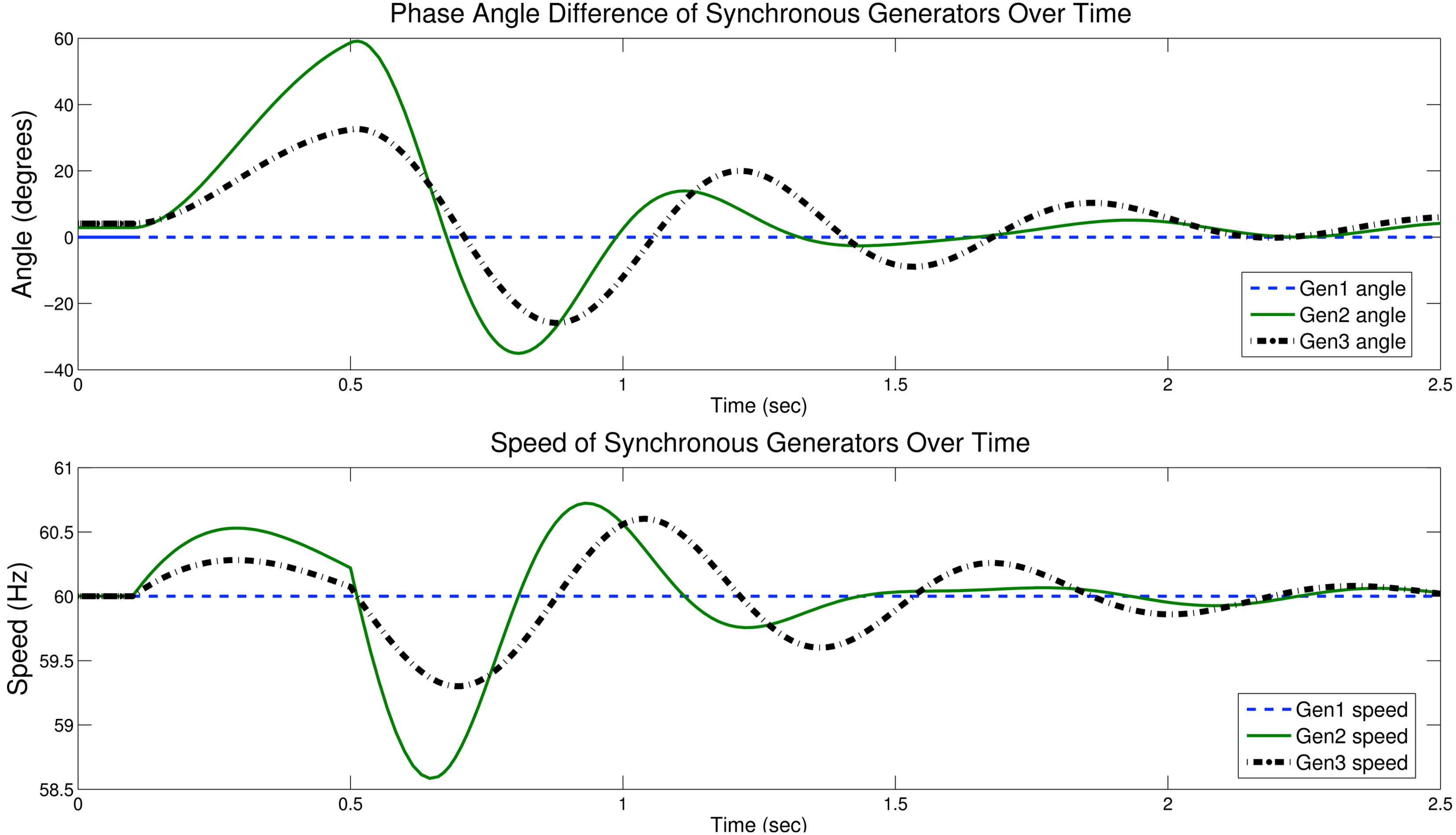
Resilient Smart Grid Simulator



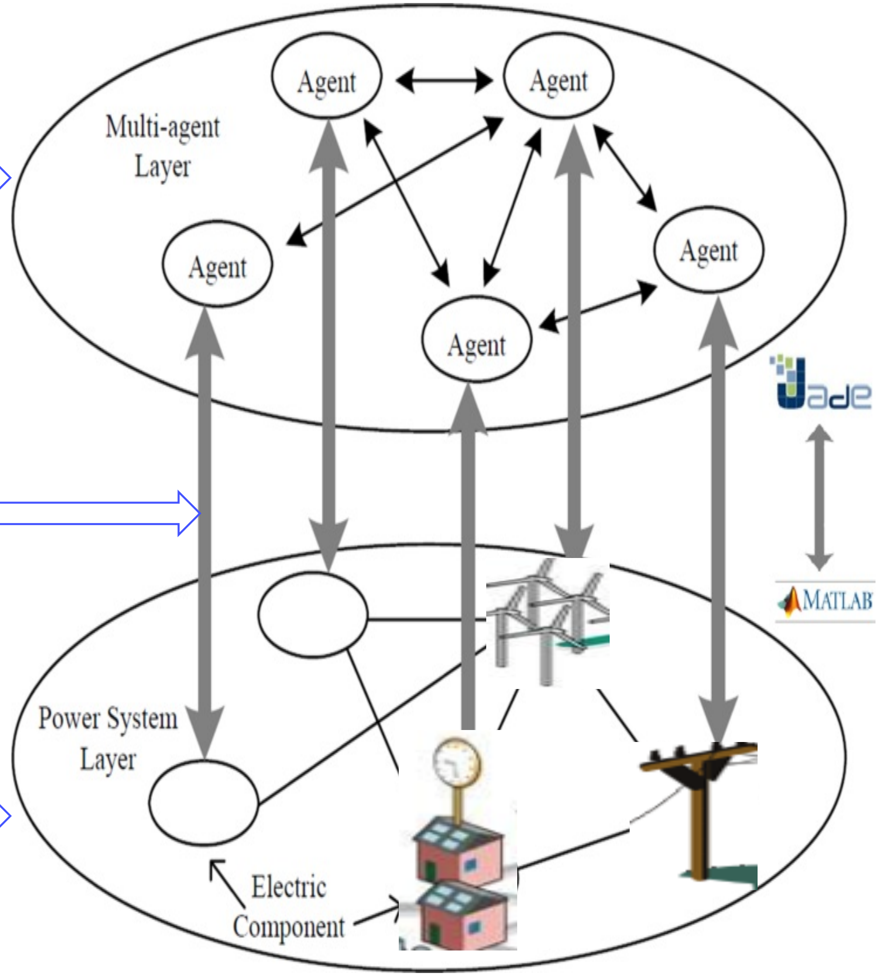
∴ **A transient stability example. Supports customized models.**

Developed Multi-Agent System Transient Stability Platform

- Multi-agent layer
- Developed in JAVA-JADE

- Each physical component has its virtual representation in multi-agent layer
- JAVA-MATLAB interface enables communication in both ways

- Power system layer
- Developed in MATLAB



∴ **Shows impact of cyber-agent negotiation on physical power grid!**

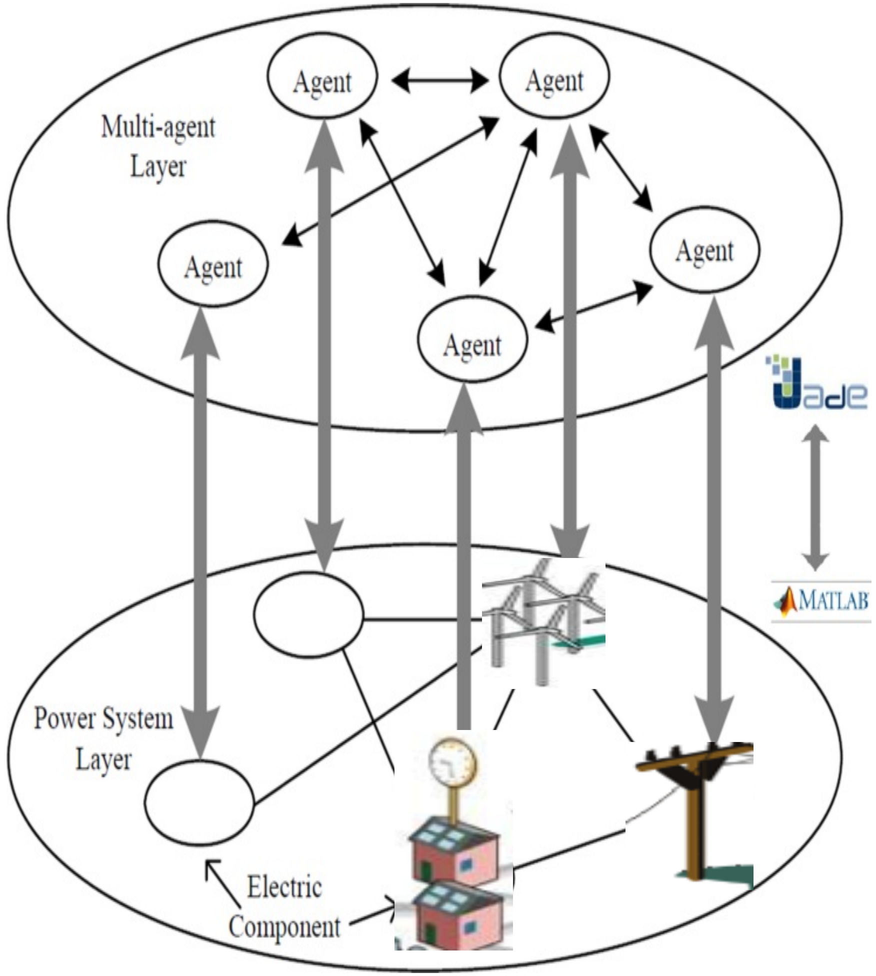
Developed Multi-Agent System Transient Stability Platform

Multi-agent layer

- MAS allows semi-autonomous decision-making
- JAVA-JADE describes parallel decision-making of each agent as multi-thread language

Power system layer

- Time domain simulation of power system transient stability
- MATLAB solves Differential Equations fast and accurately



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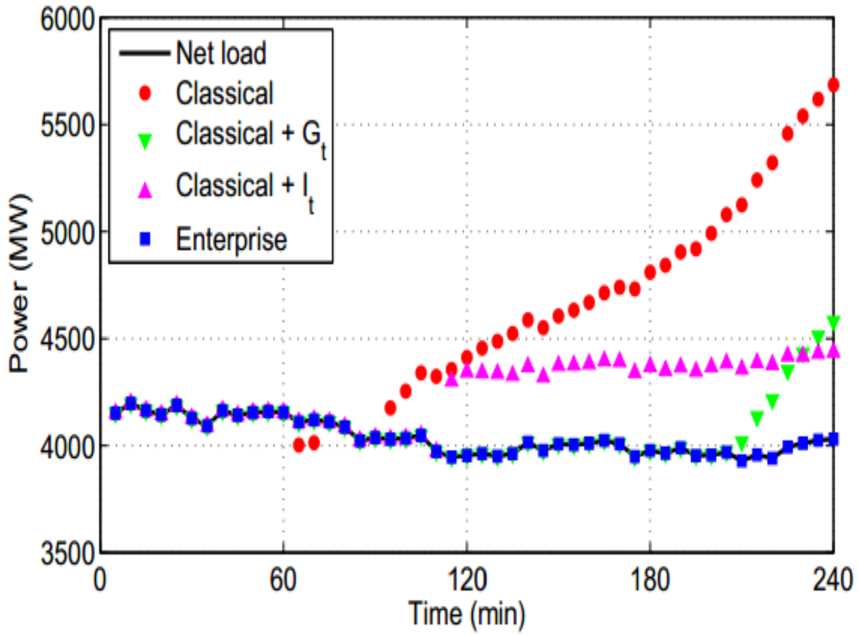
Cost optimality does not guaranteee physical system stability



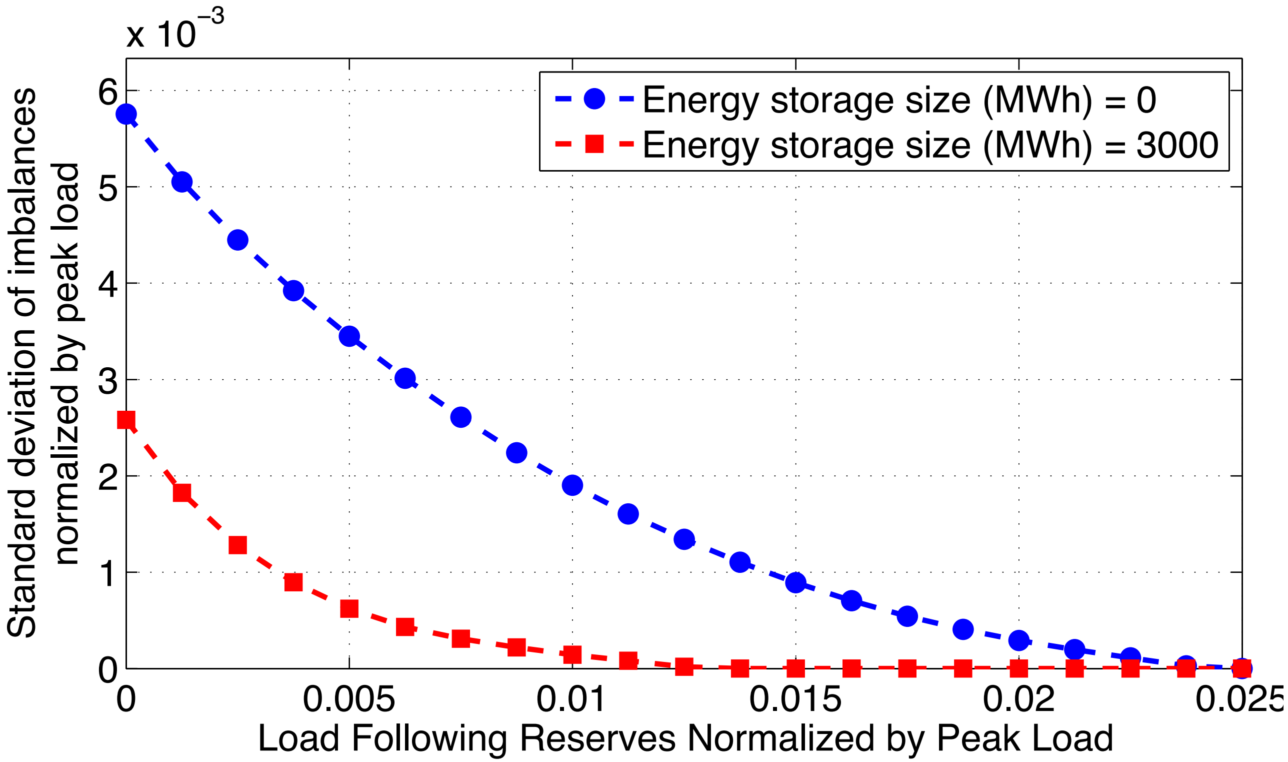
Role of cross-layer feedback in enterprise control demonstrated by a set of simulations w/ four variations of the power balance constraint:

- classical,
- classical + I_t,
- classical + G_t,
- enterprise control.

- For the classical method, the regulation goes to saturation quickly and the imbalance starts to accumulate.
- The presence of the $\boldsymbol{G_t}$ term alone periodically resets the utilized regulation and allows partial mitigation of the imbalance. However, the residual imbalance starts to accumulate.

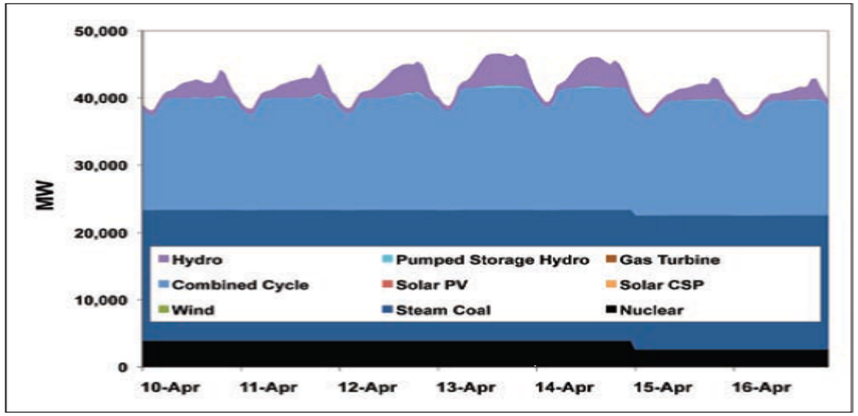
∴ The DA & RT markets are cost optimal but the system can have drastically different stability!

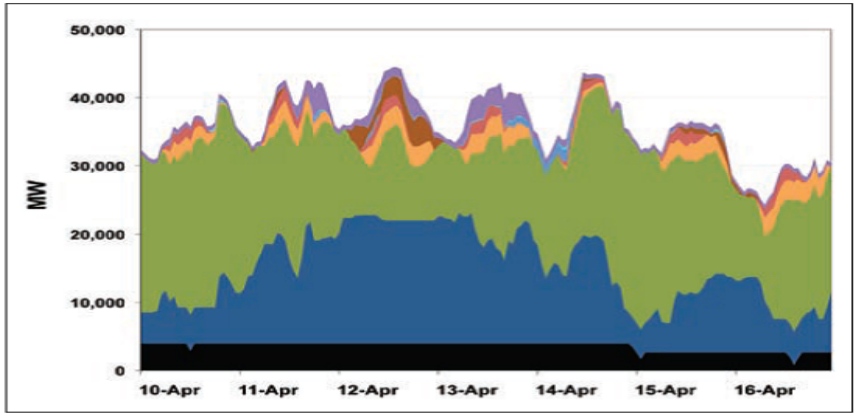
Physical system stability does not guarantee cost optimality!



∴ The same physical performance can be achieved with different combinations of resource with no change in market design.

Negotiated equilibria do not guarantee cost optimality!





- Renewable energy resources can exacerbate the load following requirement for thermal generation units!
- Greater burden on thermal unit control & ramping capability!
- Thermal unit capacity utilization & economic rationale will naturally deteriorate!

∴ When multiple time block interactions exist or are required from the physical systems, local information sometimes prevents finding global optima

Distributed decision-making does not guarantee resilience

	[47,48]	[49]	[50,51]	[52]	[53]	[54]	[55]	[56,57]
1	Model limited to lines & substations. No model for power generation & consumption.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption, and lines. No agents assigned to buses, storage, RE, or dispatchable load.	Model limited to load and bus agents.	Model addresses all power system structural degrees of freedom.
2	One physical resource has many function blocks. Each function block is meant to be part of a larger control agent.	Each agent has a physical resource. Not all physical resources have an agent.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Each agent has a physical resources. No agents are assigned to grid topology.	Some physical agents are included. Some centralized agents are included.	Some physical agents are included. Some centralized agents are included.	1-to-1 relationship of physcial agents to resources.
3	Model limited to lines & substations. No model for power generation & consumption.	Model limited to power generation, consumption & sotrage. No agents assigned to grid topology.	Model limited to power generation, consumption & sotrage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption & storage. No agents assigned to grid topology.	Model limited to power generation, consumption, and lines. No agents assigned to buses, storage, RE, or dispatchable load.	Model limited to load and bus agents.	Model addresses all power system structural degrees of freedom.
4	Does not address the aggregation of generators, loads, or power grid areas.	A grid agent is included as a single entity rather than an aggregation of multiple entities.	A microgrid manager agent is included as a centralized decision-making entity.	Centralized agents are included for centralized decision-making.	Does not address the aggregation of generators, loads, or power grid areas.	Centralized agents are included for centralized decision-making.	Centralized agents are included for centralized decision-making.	Centralized agents are included for centralized decision-making.
5	Only Line & substation availability. Generation/Consumption not included.	All agents are assumed to be online.	All agents are assumed to be online. Microgrid can operate in grid-connected and disconnected modes.	All agents are assumed to be online.	All agents are assumed to be online.	All agents except for central agent & grid agent can be unavailable.	Only Line & substation availability. Generation/Consumption not included.	All agents can be switched on/off.
6	Function block interactions exists between lines & substations but not with generation & loads.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to the topology agents, there can be no coordination between energy and topology elements or between topology elements.	Without agents assigned to buses, storage, RE and dispatchable loads, coordination decisions are limited.	Without agents assigned to other physical resources, coordinated decisions are limited.	Agent architecture does not include interaction between branches, buseses & energy elements.
7	No extraneous agent interactions have been added.	Supercondensator initiates all negotiations with other agents in a sequential fashion.	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	No extraneous agent interactions have been added.	Introduction of multiple centralized decision-making agents likely to add extra agent-to-agent communication	Facilitator acts as a centralized agent.	Introduction of centralized decision-making agent likely to add extra agent-to-agent communication

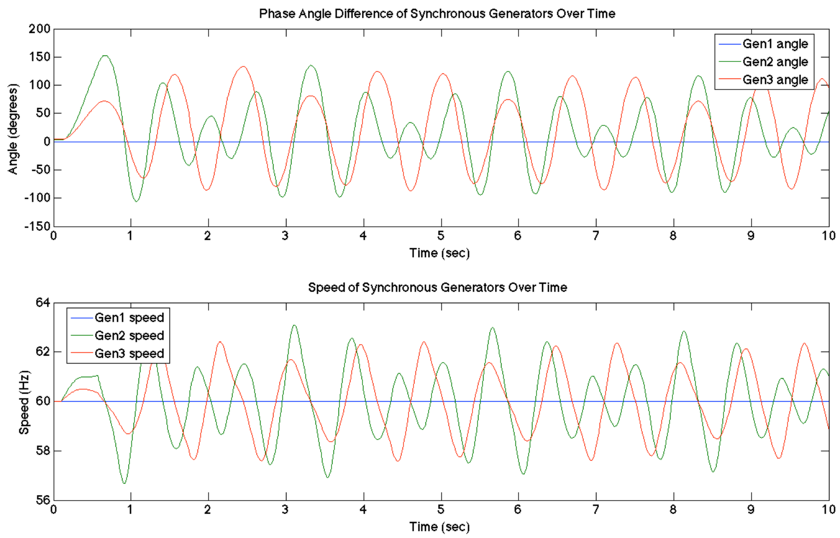
∴ Distribution is a necessary but not sufficient condition for resilience!

Distributed decision-making does not guarantee resilience

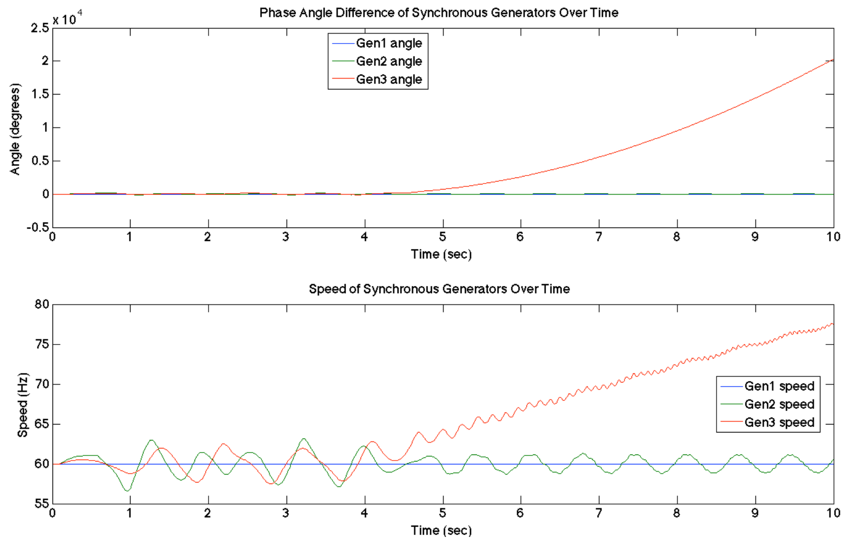
	[47,48]	[49]	[50,51]	[52]	[53]	[54]	[55]	[56,57]
8	1-many cyber-physical relation but each function block is meant to be an automation object as part of a larger control agent.	Agents are assigned to PV, storage, and external grid. No agents for loads, lines, and substations.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Some physical agents are included. Some centralized agents are included. No agents assigned to grid topology.	Each agent has a physical resources. No agents are assigned to grid topology.	Some physical agents are included. Some centralized agents are included.	Some physical agents are included. Some centralized agents are included.	1-to-1 relationship of physcial agents to resources.
9	Fulfilled.	Fulfilled.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.	Fulfilled.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.	The use of centralized decision-making causes local information to be centralized.
10	IEC61850/61499 are used with function blocks. Does not consider FIPA-compliant agents.	Matlab simevents is used for the development of MAS. Not FIPA compliant.	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents	Matlab is used for the development of MAS. Not FIPA compliant.	FIPA Compliant JADE Agents	FIPA Compliant JADE Agents
11	SimPower Systems Model but specifics are not mentioned.	Physical model of a DC grid implemented in simulink.	Real-Time Digital Simulator/Power World Simulator as physical model.	Small-signal stability model implemented in Matlab.	Real-time diesel generator included.	Physical model of system implemented in Matlab	Physical system model of implemented in Matlab/Simulink w/o specifices.	Transient stability physical model implemented in Matlab.
12	Function blocks are intended as real-time execution agent for fast switching decisions.	None present.	None present.	f-V and P-Q controls implemented as real-time execution agents.	Governor control implemented as real-time execution agent.	Voltage and PQ control implemented as real-time execution agents.	None present.	Automatic Generation Control & Automatic Voltage Regulators implemented real-time execution agents.
13	Slower timescales are not considered	Coordination agents address energy-management functionality.	Coordination agents address energy-management functionality.	Middle level coordination and high level energy management agents address balancing and voltage control operation	Coordination agents address energy-management functionality.	Central agent address black start service.	Central agent addresses restoration service.	Coordination agents address energy-management functionality.
14	Since only one time scale is considered, function-block layer is flat.	Since only one time scale is considered, agent architecture is flat.	Energy management is considered for the day-ahead and real-time markets. Power grid dynamics are not.	Three layer agent hierarchy devoted real-time frequency control, voltage coordination and energy management.	Two layer control hierarchy: energy management & real-time frequency control.	Two layer control hierarchy: black start coordination & real-time control.	Since only one time scale is considered, function-block layer is flat.	Two layer control hierarchy: energy management & real-time control.
Decision	Fault Location, Isolation & Supply Restoration	Energy management	Energy management	Energy management, voltage control, small-signal stability	Energy management & Frequency Control	Black start coordination & Real-Time Control	Restoration Service	Energy management & Frequency Control
Implementation	IEC61499 Function Block Implementation w/ SimPower Systems Simulation	Matlab Simevents/Simulink Implementation	JADE Agents with Real Time-Digital Simulator/Power World Simulator	JADE Agents with Small-Signal Stability Matlab Simulator	JADE Agents with Real-Time JAVA simulation	Matlab Implementation	JADE Agents with Simulink/Matlab Simulator	JADE Agents with Transient Stability Matlab Simulator

∴ Distribution is a necessary but not sufficient condition for resilience!

Switching decisions require RT control for transient stability!



(a) Time Domain Simulation w/ 0.58s Fault Clearing Time [53]



(b) Time Domain Simulation w/ 0.59s Fault Clearing Time [53]

∴ A 0.01s delayed decision makes all the difference!

Thank You